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Landscape-Scale Tree Growth Dynamics at Three Southern West Virginia National Parks

Bluestone National Scenic River, Gauley River National Recreation Area, and New River Gorge National River

Natural Resource Report NPS/ERMN/NRR—2020/2123

ON THIS PAGE
The New River Gorge at Fayette Station.
Photography by: Thomas Saladyga

ON THE COVER
Mixed hardwood forest on the upper slopes of the Bluestone National Scenic River.
Photography by: Thomas Saladyga

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Executive Summary

We used tree core samples collected between 2015 and 2018 at 186 long-term forest monitoring plots distributed across three National Park Service units in southern West Virginia (Figure 1) to assess landscape-scale climate-tree growth relationships and patterns of canopy gap disturbance. We must stress that the tree core samples analyzed herein were not collected with these objectives in mind. Therefore, our analyses and interpretation of results should be viewed in the context of potential applications for regional tree-ring datasets, rather than as the final word on local forest patterns and processes.

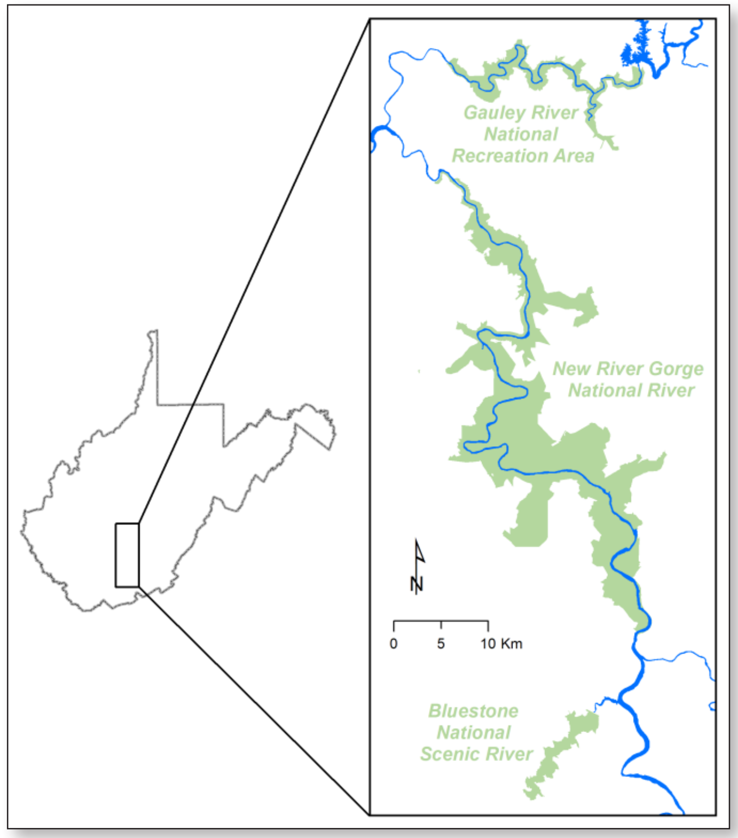

Figure 1. Location of Bluestone National Scenic River (BLUE), Gauley River National Recreation Area (GARI), and New River Gorge National River (NERI) within the state of West Virginia.

Specifically, our investigation answered the following questions:

What are the climatic drivers of growth in three dominant, or common, tree species, *Liriodendron tulipifera* L. (tuliptree or poplar), *Quercus alba* L. (white oak), and *Quercus prinus* L. (chestnut oak)?

> Tree growth of dominant species is positively correlated with moisture in the current growing season (May – August) and previous growing season (July – October). Tree growth in the study region is responsive to climate over the broader central portion of the eastern United States.

How have climate-tree growth relationships changed over time?

> The tree growth response to climate shifted over time in *Quercus* species with decreasing positive correlations to current growing season moisture and increasing positive correlations to previous growing season moisture. *L. tulipifera* growth-climate relationships remained mostly stable. Shifts in the growth response to climate are linked to significant shifts in moisture in June and August.

Does the timing and spatial extent of canopy gap disturbance vary across Park units or by terrain position?

> There is little evidence of spatial clustering of canopy gap disturbance at BLUE, GARI, and NERI during the 20th century, suggesting that canopy gap disturbance typically occurred in a random spatial pattern, consistent with the concept of small gap formation in closed-canopy deciduous forests. Canopy gap disturbance is dependent on terrain position, with more growth releases occurring than expected at plots located on steep slopes. For all plots combined, canopy gap disturbance was most extensive during the 1930s, 1960s, 1970s, and 1990s.

Based on our results, what additional research questions might be addressed with more systematic data collection, either at the landscape or local scale?

> We suggest that targeting species with low representation in the data set (e.g., eastern hemlock, eastern white pine, and red maple) would provide a fuller understanding of the variable response of tree species to changes in climate both past and present. A second method for expanding the analysis would be to include tree core data from throughout the central Appalachian region. In addition, systematic sampling (e.g., large plots) would be necessary to improve our understanding of past disturbances at multiple spatial scales.

Acknowledgements

We acknowledge the dedicated work of Doug Manning and all of the ERMN field crew members in the collection of tree core samples during the 2015-2018 field seasons. We are grateful to Warren Reed, Erynn Maynard, and Dr. Margot Kaye of the Pennsylvania State University for sanding, mounting, and reading hundreds of tree cores. We also thank Matt Marshall for access to and use of these data.

Introduction

Understanding the effects of climate on forest dynamics is essential to protect and manage forest resources in national parks. Tree-growth rings provide important information on the relationships among climate, forest productivity, and forest disturbance. Specifically, annual, and in some cases seasonal growth rings can be used to identify past forest disturbances and extreme weather events, as well as establish relationships between climate variability and tree growth (Speer, 2010; Itter, 2017; D'Amato, 2013).

In this study, we used tree core samples collected between 2015 and 2018 at 186 Eastern Rivers and Mountains (ERMN) forest monitoring plots distributed across three National Park Service units in southern West Virginia to assess landscape-scale climate-tree growth relationships and patterns of canopy gap disturbance. We must stress that the tree core samples analyzed herein were not collected with these objectives in mind. Therefore, our analyses and interpretation of results should be viewed in the context of potential applications for regional tree-ring datasets, rather than as the final word on local forest patterns and processes.

Specifically, we asked the following questions:

1. What are the climatic drivers of growth in three dominant tree species, *Liriodendron tulipifera* L. (tuliptree or poplar), *Quercus alba* L. (white oak), and *Quercus prinus* L. (chestnut oak)?
2. How have climate-tree growth relationships changed over time?
3. Does the timing and spatial extent of canopy gap disturbance vary across Park units or by terrain position?
4. Based on our results, what additional research questions might be addressed with more systematic data collection, either at the landscape or local scale?

Methods

Study Area

This study used tree core samples previously collected by ERMN staff at three National Park Service (NPS) land units located on the Allegheny Plateau in southern West Virginia (WV) (Figure 1; Table 1). These include Bluestone National Scenic River (BLUE), Gauley River National Recreation Area (GARI), and New River Gorge National River (NERI). The region is characterized by dissected stream valleys and, in some locations, steep river gorges such as those found within the three Park units. Forests are predominantly mixed mesophytic with species composition influenced by the complex topography of the region. Dry oak (*Quercus* spp.) and pine (*Pinus* spp.) forests that dominate the ridges, southern facing slopes, and cliff edges, contrast with maple (*Acer* spp.), American beech (*Fagus grandifolia* Ehrh.), and eastern hemlock (*Tsuga canadensis* (L.) Carrière) that occupy cool, moist northern facing slopes (Vanderhorst et al., 2007). Moving downslope, these forests give way to cove forests, floodplain forests, and Appalachian flatrock communities along the New and Gauley Rivers (Vanderhorst et al., 2007). Climate in the region is humid continental with an average annual temperature of 9.7°C and monthly temperatures ranging from 20.4°C in July to -2.0°C in January (1981-2010; NOAA, 2018). Average annual precipitation is 124.4 cm, ranging from 13.3 cm in July to 8.2 cm in October (1981-2010; NOAA, 2018). The climate across West Virginia and the region in general has become increasingly wet and temperate since the 1960s (Kutta and Hubbart, 2018).

Bluestone National Scenic River

BLUE was established as a "Wild and Scenic River" in 1988. The park, located in Summers County, WV, encompasses approximately 1,750 hectares of mixed mesophytic and dry oak-pine forests and protects approximately 17 km of the Bluestone River. This study utilized tree cores collected at 41 plots within the park. Slope at these plots ranges from flat to 60%, with an average of nearly 27%, while elevation ranges from 432 m to 697 m, with an average of 555 m (Table 1).

Gauley River National Recreation Area

GARI was also established in 1988. It contains approximately 4,500 hectares of rugged terrain along 40 km of the Gauley River in Fayette and Nicholas Counties, WV. This study utilized tree cores collected at 43 plots within the park. Slopes are significantly steeper than those found at BLUE and slightly steeper than slopes at NERI, with values ranging from 6% to 60%, and an average of 37%. Elevation ranges from 290 m to 556 m, with an average of 431 m (Table 1).

New River Gorge National River

Established in 1978, NERI encompasses approximately 30,000 hectares of mixed mesophytic and dry oak-hickory forests along 85 km of the New River. The largest of the three parks in southern West Virginia, NERI stretches from Hawks Nest Lake north of US 19 in Fayette County to the Bluestone Dam south of Interstate 64 in Summers County. This study utilized tree cores collected at 102 plots within the park. Slope at these plots ranges from 1% to 86%, with an average of 32%, while elevation is highest at NERI compared to the other two parks, ranging from 336 m to 958 m, with an average of nearly 637 m (Table 1).

Table 1. Eastern Rivers and Mountains Network plots used in the analyses at Bluestone National Scenic River (BLUE), Gauley River National Recreation Area (GARI), and New River Gorge National River (NARI). Mean slope and elevation values (± 1 standard deviation) for plots within each Park unit are included for reference.

Park Unit	Number of plots	Slope (%)[1]	Elevation (m)[1]
BLUE	41	26.5 ± 17.5*	555.2 ± 83.8*
GARI	43	37.1 ± 20.0^	431.1 ± 64.8^
NERI	102	32.1 ± 19.2	636.5 ± 150.0†

[1]Values are presented as mean ± 1 standard deviation. Means in a column with different symbols (*,^,†) are significantly different ($p < 0.05$) based on ANOVA and Tukey's post hoc test.

Sampling Design

Tree core samples were collected as part of a long-term forest health monitoring program (Perles et al., 2014) that collects data at 186 permanent plots across the three national parks. These plots were randomly selected from a regular grid of potential plot locations in each park using a generalized random-tessellation stratified (GRTS) design (McDonald, 2004; Stevens and Olsen, 2004) that produces a randomly-selected, spatially-balanced list of plots. Two trees that were representative in size and species of the canopy were selected just outside of each permanent plot, and two cores were sampled from each tree. Tree core samples were collected using methods described in the ERMN Vegetation and Soil Monitoring Program Standard Operating Procedures, version 7.0 (2015).

This sampling design differs in several ways from most tree-ring studies. First, tree cores were sampled from randomly located dispersed sites across a large study area, as opposed to sampling many trees in a localized area. Second, cored trees were representative of the surrounding forest instead of intentionally targeting a single species, or the oldest or largest trees in an area.

Tree-Ring Data

Cores were mounted and sanded to reveal ring boundaries according to standard dendrochronological practice (Speer, 2010). Annual ring widths were measured using a Velmex measuring stage (Velmex, Inc.) in conjunction with MeasureJ2X software (Voortech Consulting, Holderness, NH, USA). Ring width measurements were crossdated using the program COFECHA, which assesses the statistical accuracy of dating and allows for correction of misdated time series (Holmes, 1983).

Typically, tree-ring chronologies are developed for a single species growing in a single forest stand or region. The diversity of tree species in the ERMN tree core data set necessitated that we focus on the most abundant species sampled to achieve a sample size adequate for analysis and representative of the dominant species growing in the parks. Subsequent analysis focused on three tree species – *Quercus alba* (white oak), *Quercus prinus* (chestnut oak), and *Liriodendron tulipifera* (tulip tree or yellow poplar). We combined samples together for each species growing across the three parks. While this is a wide geographic range, individuals from a species are known to crossdate across a wider region because climate is a predominant limiting factor to the annual growth of trees in mid-latitude forests (Fritts, 1976).

Raw ring-width measurements for each species were detrended for climate analysis using the dplR package in the R programming language (Bunn, 2008). We applied a two-thirds smoothing spline to remove growth trends related to biological growth changes over time and to minimize the influence of disturbances (Cook, 1985). Temporal autocorrelation in the tree-ring time series was removed using an autoregressive model resulting in a residual time series for each tree core. Then, a robust bi-weight mean chronology was calculated for each species to highlight common inter-annual variability (Cook and Kairiukstis, 2013). The residual chronologies for each of the three dominant tree species were used for subsequent climate analysis. Please note that raw ring-width data were used in the disturbance detection analysis.

Climate Data

Annual ring width of trees growing in temperate climates is controlled by a combination of tree age, forest disturbance, and climate. In climate analysis, it can be difficult to parse the influence of precipitation and temperature on the availability of water to the tree. Therefore, we chose to investigate the influence of the drought metric, Standardized Precipitation Evapotranspiration Index (SPEI), which incorporates both temperature and precipitation to determine the influence of water stress on vegetation (Vicente-Serrano et al., 2010; Figure 2). The SPEI data were calculated and downloaded from the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer (Trouet and Van Oldenborgh, 2013) for the region encompassing BLUE, GARI, and NERI for the 1902 – 2013 period. SPEI can be calculated with known lag effects of 1 – 48 months to better understand the cumulative effect of drought on vegetation. We choose to investigate mean June-August SPEI with a 3-month lag to assess short-term or seasonal effects of drought on annual ring width.

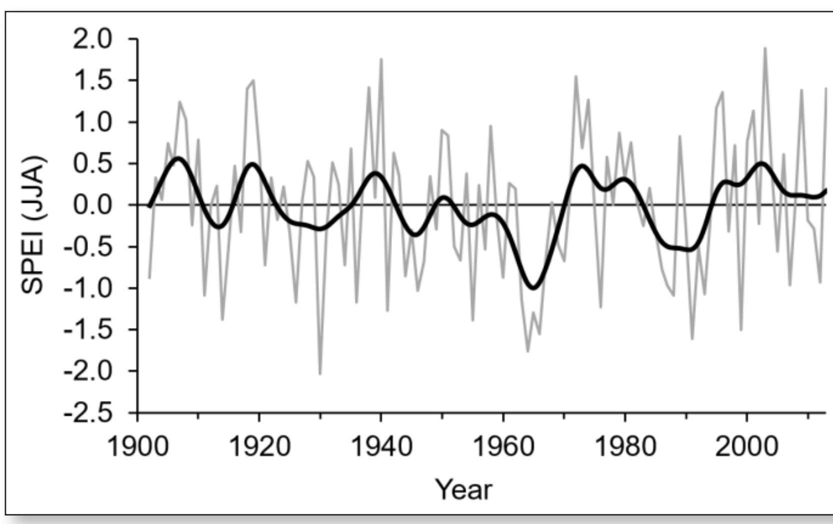

Figure 2. Mean June – August Standardized Precipitation Evapotranspiration Index (SPEI; 3-month lag) for the southern region of the Eastern Rivers and Mountains Network park system (1902-2013). Values (gray line) greater than zero indicate above average conditions (pluvial) and values below zero indicate below average conditions (drought). The time series is smoothed with a 20-year Gaussian filter (thick black line) to highlight longer-term trends in SPEI.

We assessed the time stability of the contemporary SPEI climate data using regime shift analysis (Rodionov, 2004). A regime shift is a significant shift in the mean or variance of a time series from one period of comparison to another. To identify a regime shift, running means were calculated using 20-year windows. Adjacent 20-year windows were assessed for a difference in means using a standard t-test and an alpha significance level of 0.10.

Climate-Tree Growth Relationships

We assessed the relationship between annual ring width and drought in the treeclim package in R (Zang and Biondi, 2015). The treeclim package allows for the investigation of both static and moving correlation functions to better determine how tree growth responds to changes in climate over time (Biondi and Waikul, 2004; Zang and Biondi, 2015). In the static correlation analysis, annual ring width was correlated with monthly SPEI data from the previous May to the current August for the 1902 – 2013 period. We include the climate data from the previous growing season because of the known preconditioning effect of climate in the previous year on the current year growth of trees (Fritts, 1976). In the moving correlation analysis, we used a 35-year moving window to assess how the relationship between climate and growth changed over the 1902 – 2013 period. The first 35-year window began in 1903 (to assess the lag effect of the previous year) and extended to 1937. Then, the moving window was incremented one year and the correlations were recalculated until the window ended in 2013. Confidence intervals for the correlation analysis were generated by bootstrapping the analysis 1000 times (Biondi and Waikul, 2004).

Additionally, we assessed the spatial correlation between the three tree-ring chronologies for the dominant species and SPEI (3-month lag) in the KNMI Climate Explorer (Trouet and Van Oldenborgh, 2013). The spatial correlation analysis allowed for an assessment of the broader influence of climate on tree growth in the WV ERMN parks. In this analysis, we correlated the residual chronology for each dominant tree species with the gridded SPEI data across the eastern United States. A broader "climate footprint" would indicate that trees are responding to climate variability outside of the WV ERMN region (Maxwell et al., 2017).

Canopy Gap Disturbance

While climate is the predominant factor controlling tree growth in arid and/or cold regions, forest disturbances (e.g., individual to group tree fall, insect outbreaks, wildfire) may be a more important factor in temperate closed-canopy forests. Forest disturbances are often recorded as growth releases in uninjured and/or surviving trees (Figure 3). We identified growth releases in individual tree cores using the radial-growth averaging (GA) method (Lorimer and Frelich, 1989; Nowacki and Abrams, 1997). To detect a disturbance, the GA method calculated the average growth over the preceding 15-year period (M1; includes the target year) and the average growth over the subsequent 15-year period (M2; excludes the target year). Then, percent growth change was calculated as in Equation 1. We required a growth increase of 25% lasting for 5 years in a row for a release to be identified. The five-year requirement also minimized the likelihood of detecting growth releases related to short-term fluctuations in climate. To minimize the detection of multiple releases stemming from a single disturbance event, we required a ten-year gap between release events. The analysis was conducted in the TRADER package in R (Altman et al., 2014).

Eq. 1 $\text{Percent Growth Change} = (M_2 - M_1) / M_1 * 100$

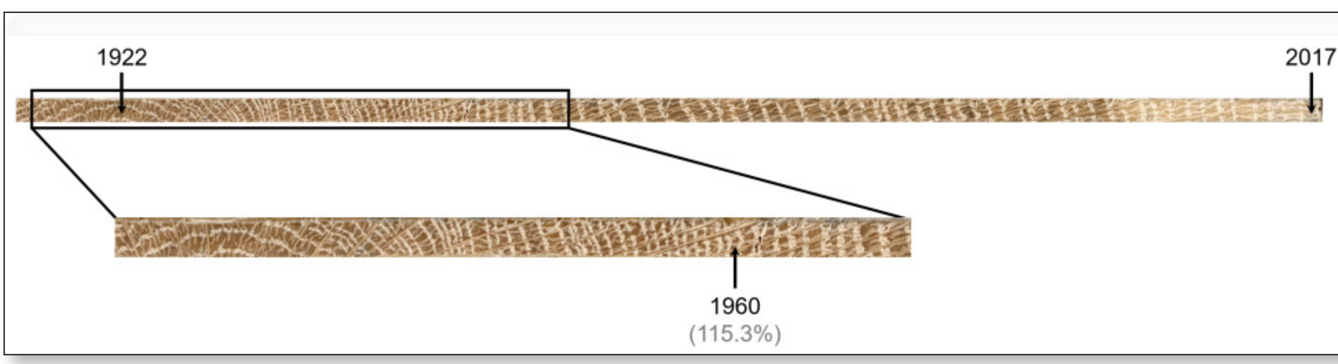

Figure 3. *Q. prinus* core sample collected at New River Gorge National River (NERI072A1). The inner-ring was dated to 1922 and the outer-ring year is 2017 (bark missing). A 115.3% growth release was identified for the year 1960.

Growth release data for individual core samples collected from 29 different tree species were subsequently scaled up to the tree and then plot level for analyses of the timing and spatial extent of canopy disturbance. This process was necessary to avoid double counting (and artificially inflating) growth releases at a plot if two samples collected from one tree recorded a growth release in the same year. Next, the number of growth releases per tree per plot were tallied for each decade between 1900 and 2000 (n = 11 decades). Note that a maximum of two cores from each of two trees were sampled at each plot, however an individual tree could experience multiple growth releases within a decade. We determined that a plot was "online" beginning in the first full decade that contained at least one tree core sample. Therefore, the number of "online" plots predictably increases with time as sample depth also increases. These data were then mapped in ArcGIS 10.7 (ESRI) for each park unit and decade of analysis. We used the Spatial Analyst extension in ArcGIS 10.7 (ESRI) to calculate Moran's Index (MI) for each decade in order to assess spatial autocorrelation, or degree of clustering or dispersion of growth release values. In addition, we calculated the relative spatial extent of canopy gap disturbance by dividing the number of plots recording a growth release by the number of "online" plots per decade for each Park unit. We used Chi-square goodness-of-fit tests to assess the distribution of the percentage of plots recording a growth release by comparing the ratio of observed to expected values per decade. We assumed expected values to be equal across decades in proportion to the number of years in each decade (There were only three years during the most recent decade (2000) when a growth release was possible due to the 15-year analysis window.).

To address our question regarding canopy gap disturbance and terrain position, we obtained the Ecological Land Unit (ELU) spatial dataset from the Natural Resources Analysis Center at West Virginia University (NRAC, 2012). This dataset stratifies the landscape based on terrain variables such as slope, elevation, and drainage, which we used to group ERMN plots for subsequent analyses (Table 2). We used the "Multi Values to Points" tool in ArcGIS 10.7 (ESRI) to extract and append ELU values to the plot point data. Nearly half of all plots were in the "Steep Slope" and "Sideslope" ELU classes, while other important ELUs include "Upper Slope" and "Cove." Similar to our analyses of the spatial extent of canopy gap disturbance, we used a Chi-square goodness-of-fit test to assess the distribution of the number of growth releases per tree for plots in each ELU. We assumed expected values to be equal across ELUs in proportion to the number of plots in each ELU class.

Table 2. All Eastern Rivers and Mountains Network plots analyzed at Bluestone National Scenic River (BLUE), Gauley River National Recreation Area (GARI), and New River Gorge National River (NERI) stratified by Ecological Land Unit (ELU) (NRAC, 2012). Mean slope and elevation values (± 1 standard deviation) for plots within each ELU are included for reference.

Ecological Land Unit	Number of plots	Percentage of plots	Slope (%)	Elevation (m)
Cliff	12	6.9	57.8 ± 15.1	516.3 ± 111.2
Steep Slope	37	21.3	51.8 ± 16.8	530.0 ± 113.6
Slope Crest	17	9.8	25.3 ± 10.8	600.6 ± 130.2
Upper Slope	18	10.3	29.5 ± 12.8	593.7 ± 158.5
Flat Summit	7	4.0	10.4 ± 4.9	616.6 ± 133.8
Sideslope	46	26.4	28.9 ± 13.7	588.6 ± 167.0
Cove	24	13.8	27.0 ± 10.3	523.7 ± 118.6
Dry Flat	3	1.7	4.3 ± 2.5	786.0 ± 93.6
Moist Flat	7	1.7	6.3 ± 5.3	678.1 ± 197.3
Wet Flat	4	2.3	13.0 ± 9.8	501.0 ± 171.6
Slope Bottom	3	1.7	3.3 ± 1.2	566.7 ± 176.7

Lastly, we compared temporal trends in growth release data at NERI to existing fire history data (see Saladyga et al., 2019), regional drought (SPEI), and population density for Fayette County (US Census Bureau, 2018) during the time period 1900-2017. Data for three fire history sites were combined to generate a landscape fire index by dividing the sum of site fire indices for each year (proportion of trees scarred) by the number of sites with at least four samples in that year (Taylor et al., 2016; Saladyga and Standlee, 2018). This fire index provides an estimation of fire occurrence and extent at NERI, but should be interpreted with caution since it is based on data from only three sites with limited sample depth. We were not able to make similar comparisons at BLUE or GARI due to the absence of site-specific fire history data.

Results

Tree-Ring Chronologies

The *L. tulipifera* tree-ring chronology began in 1855 but sample depth was not adequate for analysis until the 20th century when sample depth exceeded ten trees (Figure 4a). Overall, the *L. tulipifera* chronology had a mean interseries correlation of 0.47 and a mean sensitivity of 0.35. The *Q. alba* tree-ring chronology began in 1791 with adequate sample depth starting in the late 1800s (Figure 4b). The *Q. prinus* chronology began in 1831 with adequate sample depth starting in the late 1800s, similar to the *Q. alba* chronology (Figure 4c). Both *Quercus* spp. had similar chronology statistics with interseries correlations of 0.45 and mean sensitivities of 0.24. All of the tree-ring chronologies showed increased variability back in time as the sample depth decreased and the mean chronologies were calculated with fewer tree cores. Most of the long-term, or low-frequency, trends in the chronologies were removed during detrending but some subtle shifts in decadal variability remain.

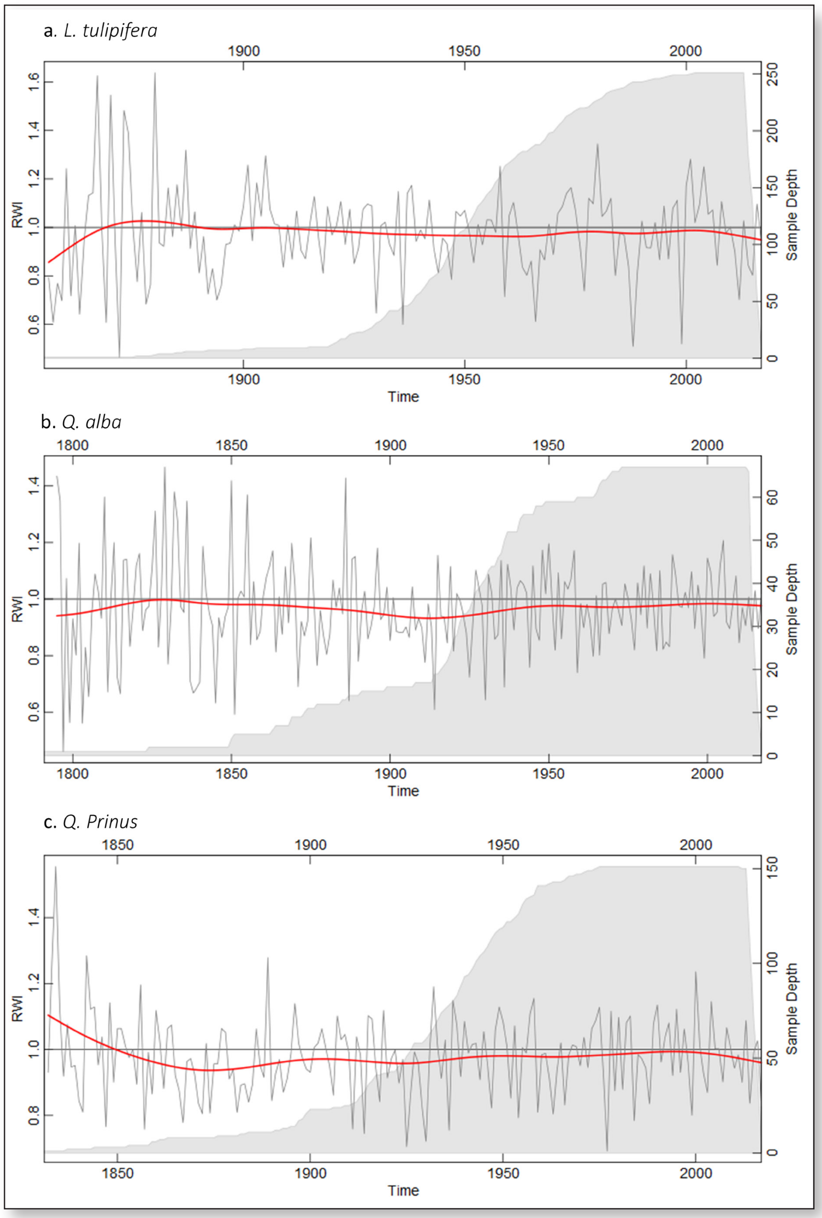

Figure 4. Residual tree-ring chronologies (solid black line) with smoothing splines showing low frequencies trends (solid red line) for a) *Liriodendron tulipifera*, b) *Quercus alba*, and c) *Quercus prinus*. The gray shaded areas represents the sample depth, or number of cores present in the dataset, over time. RWI = ring width index.

Climate-Tree Growth Relationships

Annual ring width was positively correlated ($p < 0.05$) with SPEI (drought) in the current and previous growing seasons for each of the three dominant tree species of the southern ERMN parks (Figure 5). In the static correlation analysis, *L. tulipifera* showed the strongest relationship with July SPEI in the current growing season with an $r = 0.54$ ($p < 0.05$) and r-values above 0.40 for June and August (Figure 5a). The *Quercus* species relationships to SPEI were less strong in June, July, and August ($r < 0.41$; $p < 0.05$) but remained significant (Figure 5b and 5c). The relationship to previous growing season SPEI was weaker across all species with a lack of significance for some previous summer months in the *Quercus* species (Figure 5). Interestingly, SPEI in the latter months of the previous growing season (September and October) were significantly correlated with current year growth.

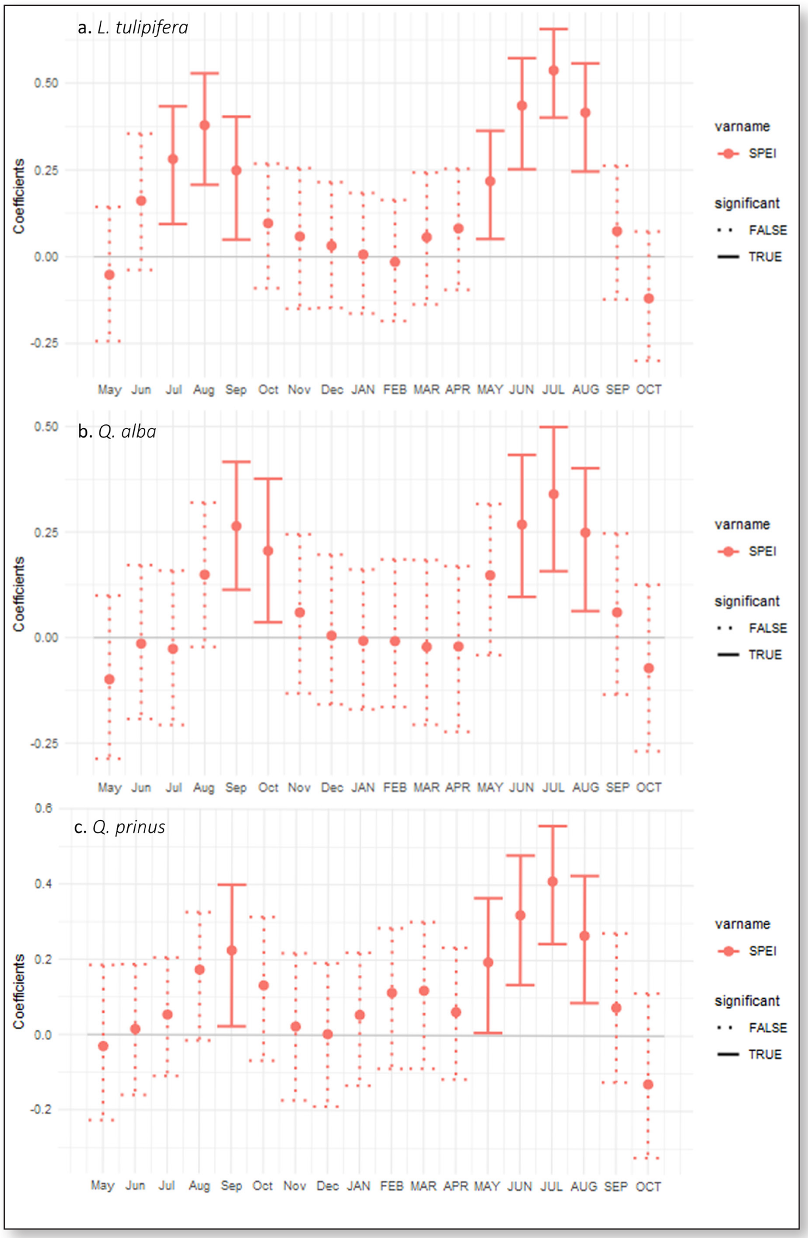

Figure 5. Static correlation coefficients showing the relationship between residual ring-width chronologies and Standardized Precipitation Evapotranspiration Index (SPEI) for a) *Liriodendron tulipifera*, b) *Quercus alba*, and c) *Quercus prinus* (1902 – 2013). On the x-axis, months ranged from the previous May to the current October. The median coefficients and the 95% confidence intervals are shown for each month. Solid lines show significant correlation coefficients.

In the moving correlation analysis, the relationship between annual ring width and SPEI showed a lack of temporal stability in many of the significant months from the static correlation analysis (Figure 6). The correlation between summer SPEI and *L. tulipifera* growth appeared to be the most time stable but a weakening in the relationship was visible. In the previous year, the relationship between *L. tulipifera* growth and drought only became significant in the 1970s. For both *Quercus* species, the relationship to current growing season SPEI faded and became non-significant from the 1980s forward (Figure 6). Similar to *L. tulipifera*, the relationship between the *Quercus* species and previous growing season SPEI only became significant in the latter half of the 20th century. Negative correlations with previous year May SPEI are likely spurious and lack a biological connection to tree growth (Figure 6).

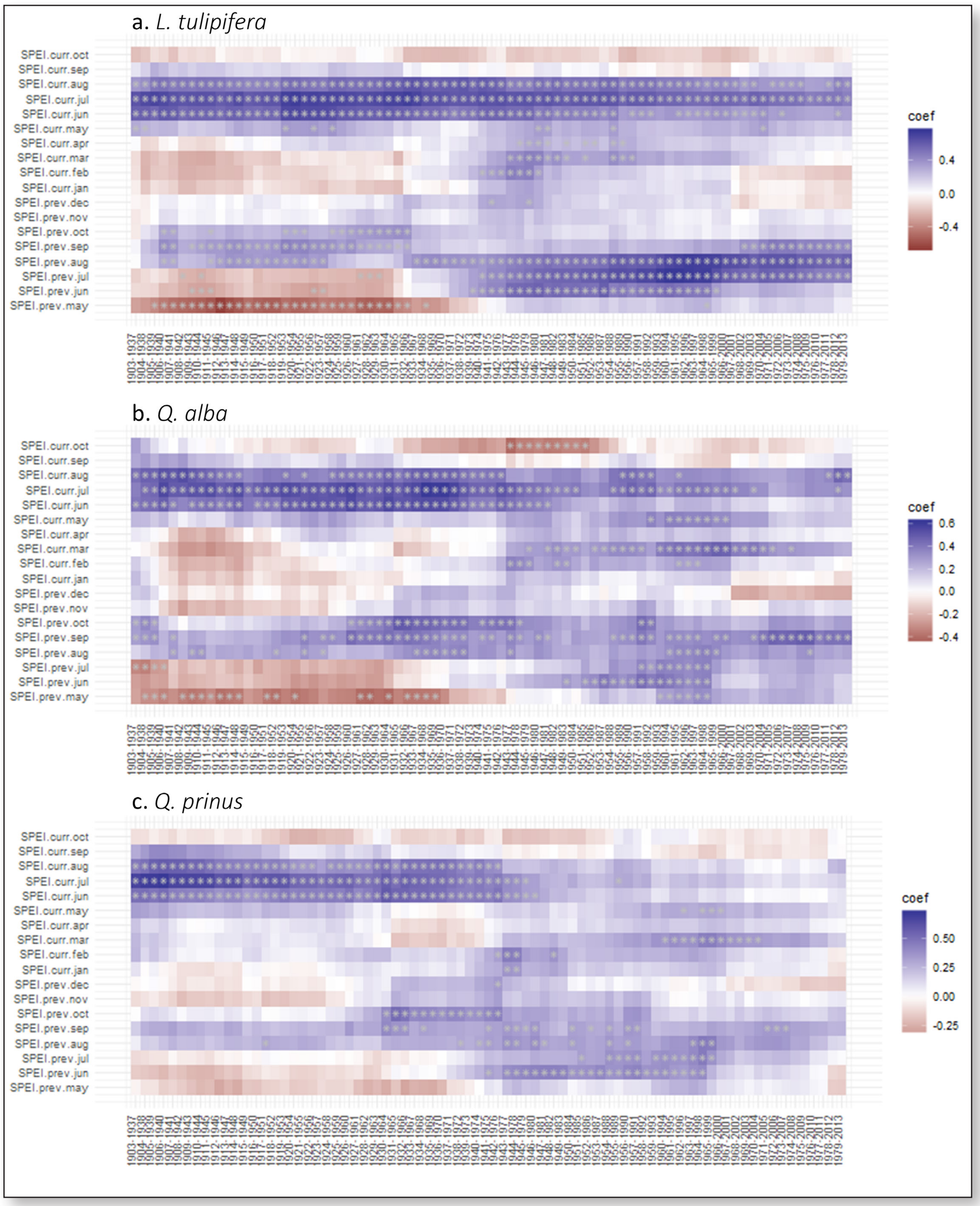

Figure 6. 35-Year moving window correlation coefficients showing the relationship between residual ring-width chronologies and monthly SPEI for a) *Liriodendron tulipifera*, b) *Quercus alba*, and c) *Quercus prinus* (1902 – 2013). On the y-axis, months ranged from the previous May to the current October. Each value in the grid represents the correlation coefficient for the end of the 35-year window. Blue colors indicate a positive correlation and red colors indicate negative correlations. Values with an * are significant a $p < 0.05$.

We further investigated the time stability of the climate data to better assess if a regime shift in the observed drought was a possible driver of the change in the correlation between growth and SPEI. Following the significant results of the climate-growth correlation analysis, we analyzed individual months of SPEI for June, July, and August individually (Figure 7). We found a significant ($p < 0.10$) shift in the mean June SPEI in 1995 when the drought metric shifted from a drier to a wetter state. There was no significant shift in the mean state of July SPEI. However, August SPEI showed a shift from a wetter mean state to a drier mean state in the 1953.

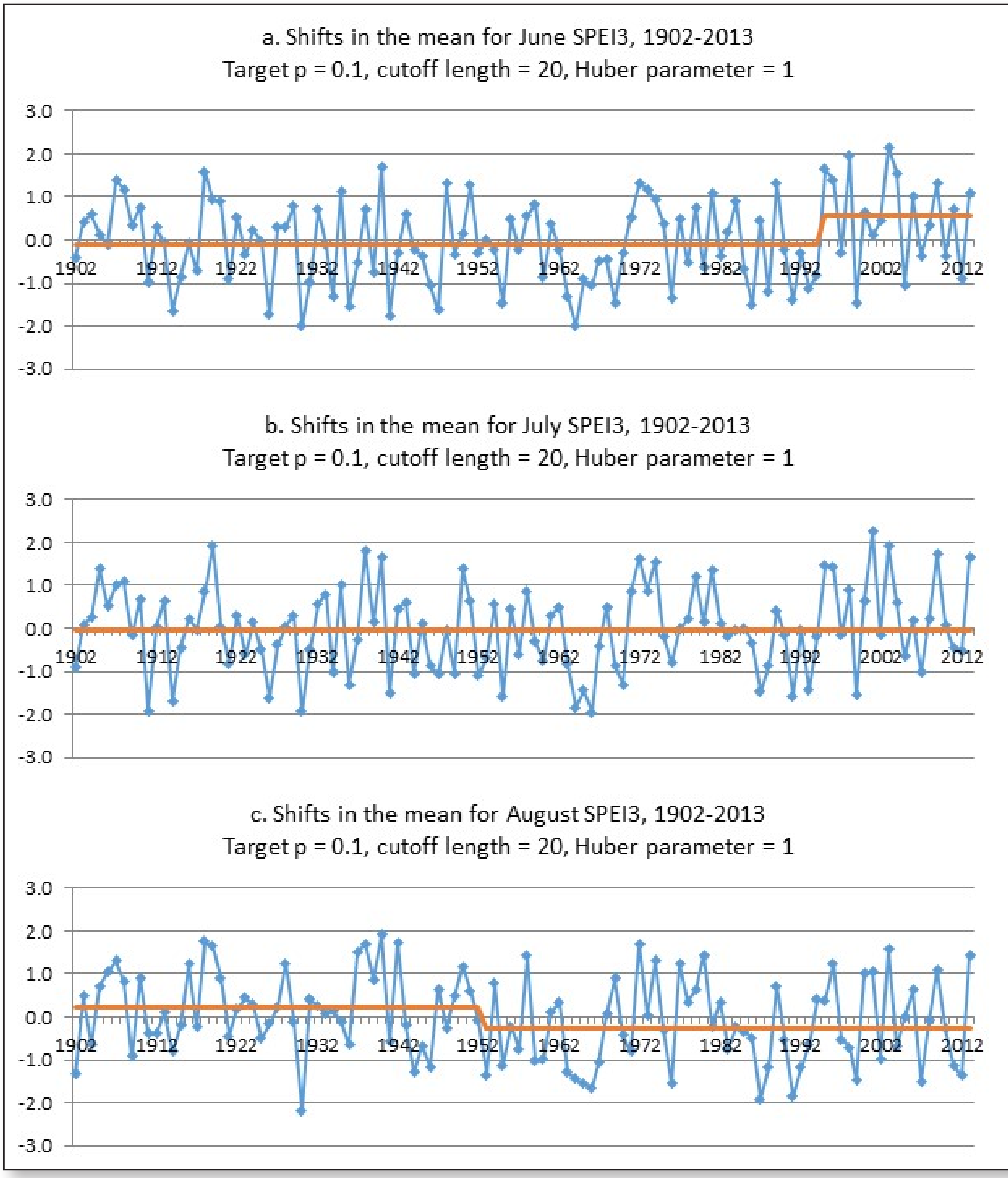

Figure 7. Regime shift analysis for June, July, and August Standardized Precipitation Evapotranspiration Index (SPEI). Values above zero represent wetter conditions while values below zero represent drier conditions. The blue line shows the annual SPEI values and the orange line shows the shifts in the mean state of SPEI.

We then investigated the spatial relationship between tree growth of the three dominant species and summer (June – August) SPEI to determine the extent to which tree growth in the study region was representative of larger climate patterns (Figure 8). We found similar climate footprints for each species showing significant correlation with SPEI through the central portion of the eastern United States.

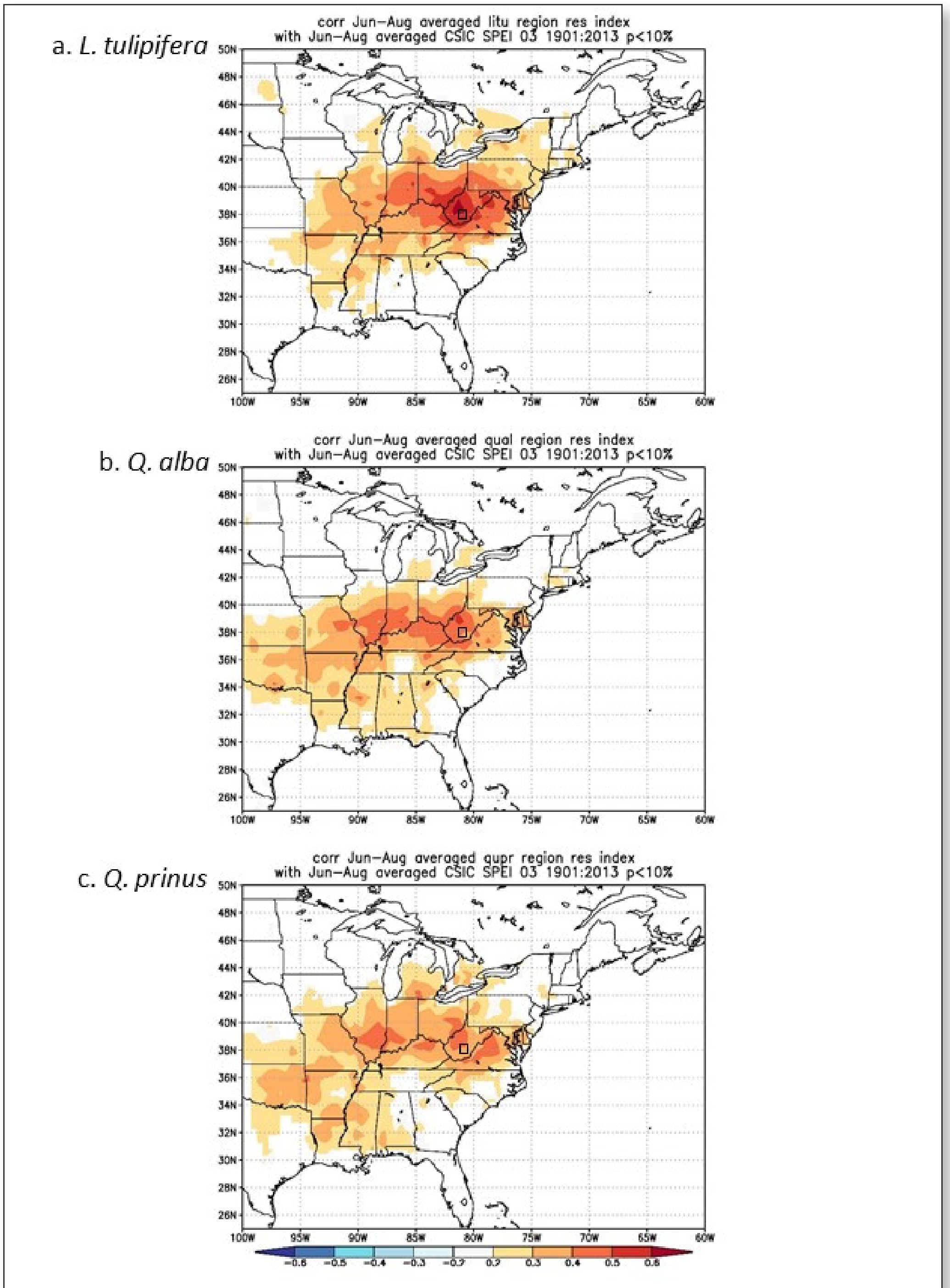

Figure 8. Spatial correlation coefficients showing the relationship between mean June – August Standardized Precipitation Evapotranspiration Index (SPEI) and residual ring-width chronologies in West Virginia for a) *Liriodendron tulipifera*, b) *Quercus alba*, and c) *Quercus prinus* (1901 – 2013). The small rectangle in WV represents the study area. Analysis and figures produced in the KNMI Climate Explorer (Trouet and Van Oldenborgh, 2013).

Canopy Gap Disturbance

The total number of tree core samples analyzed for disturbance patterns ranged from 161 at BLUE to 393 at NERI and there was no significant difference in average sample length between park units (Table 3). We found that the proportion of samples with a growth release was greatest at GARI, where the average percent growth change for detected releases was significantly higher compared to the other two park units (Table 3). Although a few samples extend back to the 17th and 18th centuries, sample depth at each park greatly diminishes by the early 20th century (Figure 9). This diminishing sample depth, therefore, justifies limiting the time frame of subsequent analyses to the 20th-21st centuries (right panel graphs in Figure 9).

Table 3. Summary growth release statistics for tree core samples collected at Bluestone National Scenic River (BLUE), Gauley River National Recreation Area (GARI), and New River Gorge National River (NERI).

Park Unit	Time period	Number of samples	Sample length (yrs)[1]	Total growth releases	Samples with growth release (%)	Growth change (%)[1]
BLUE	1791-2017	161	76.1 ± 33.7	109	47.2	100.8 ± 104.1*
GARI	1743-2017	168	77.9 ± 35.7	148	60.1	159.3 ± 265.9^
NERI	1686-2017	393	72.2 ± 33.0	271	50.9	113.2 ± 115.4*

[1]Values are presented as mean ± 1 standard deviation. Means in a column with different symbols (*,^) are significantly different ($p < 0.05$) based on ANOVA and Tukey's post hoc test.

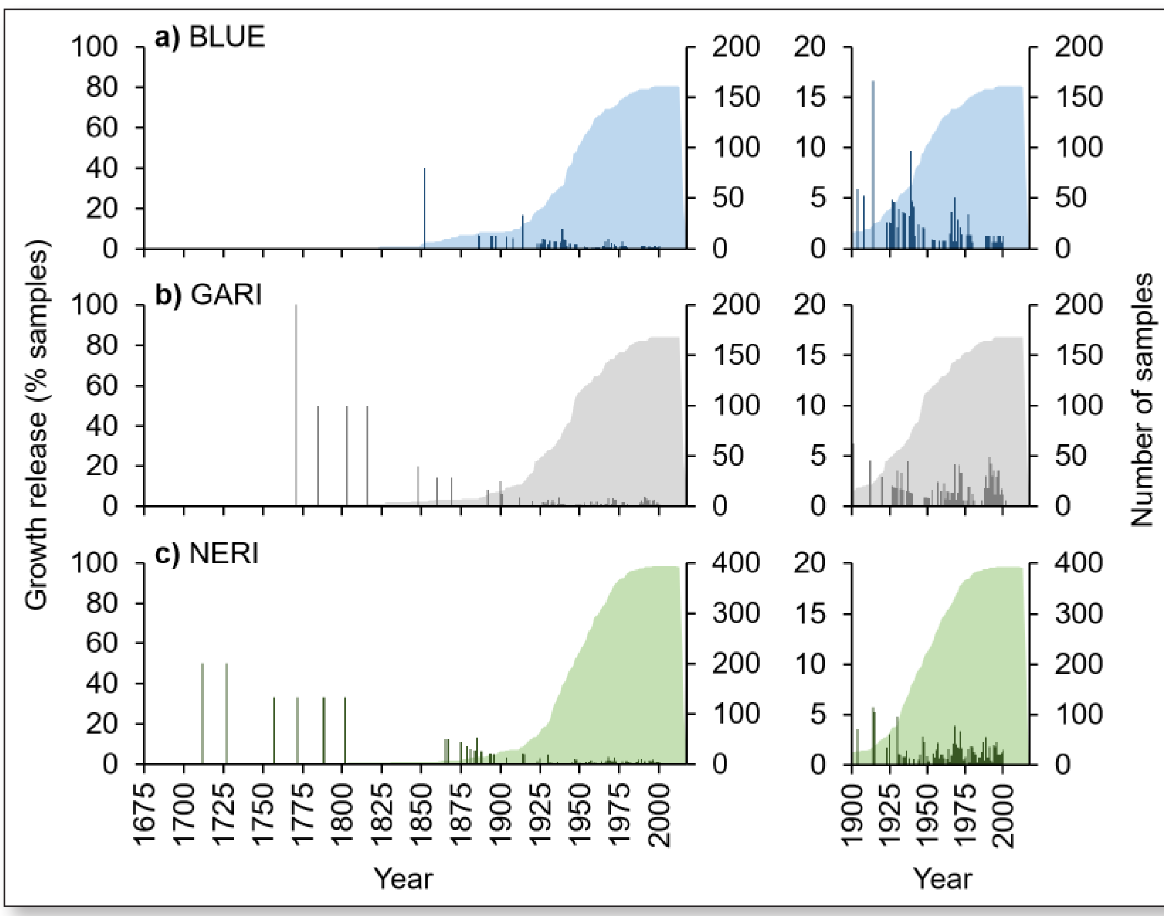

Figure 9. Annual percentage of all tree core samples recording a growth release at a) Bluestone National Scenic River (BLUE), b) Gauley River National Recreation Area (GARI), and c) New River Gorge National River (NERI). Shaded areas indicate sample depth for each Park unit. The panel on the right highlights the time period 1900-2017.

Our analyses of spatiotemporal patterns of canopy gap disturbance did not indicate significant clustering or dispersion of growth releases during most of the decades analyzed. At BLUE, however, there was significant spatial clustering of growth releases during the 1920s (MI = 0.571, $p < 0.01$) and 1970s (MI = 0.195, $p < 0.1$) (Figure 10). At GARI, there was also a significant spatial clustering of growth releases during the 1970s (MI = 0.182, $p < 0.1$) (Figure 11), while at NERI, there was significant dispersion of growth releases during the 1950s (MI = -0.131, $p < 0.1$) (Figure 12). Otherwise, canopy gap formation occurred in a statistically random spatial pattern at the three park units during all other decades.

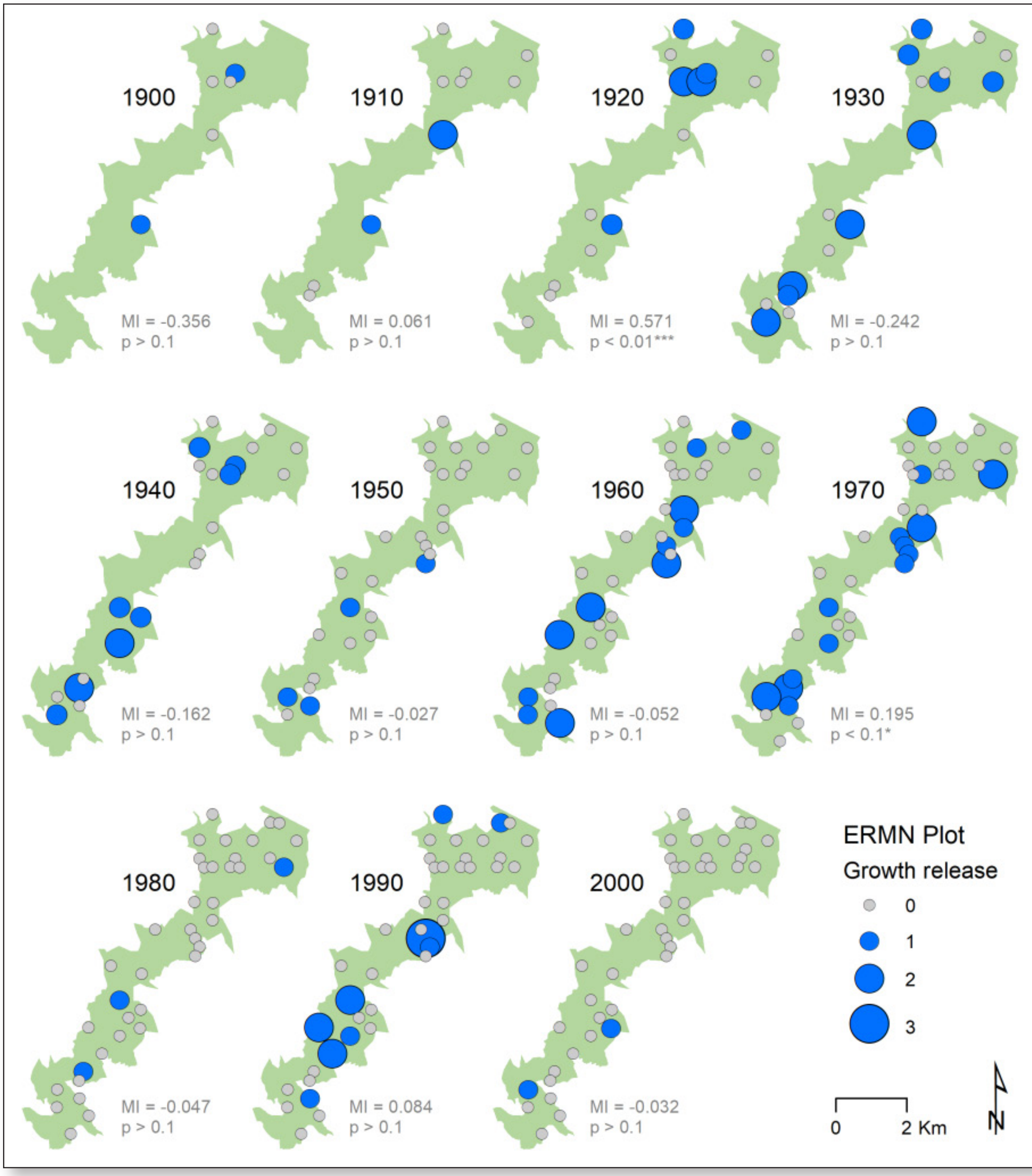

Figure 10. Spatiotemporal patterns of canopy gap disturbance (i.e., total number of tree-level growth releases per plot) at Bluestone National Scenic River (BLUE). Moran's Index (MI), a measure of spatial autocorrelation, is indicated for each decade. Data for the most recent decade (2000) should be interpreted with caution since this time period does not include the full analysis window for radial growth averaging.

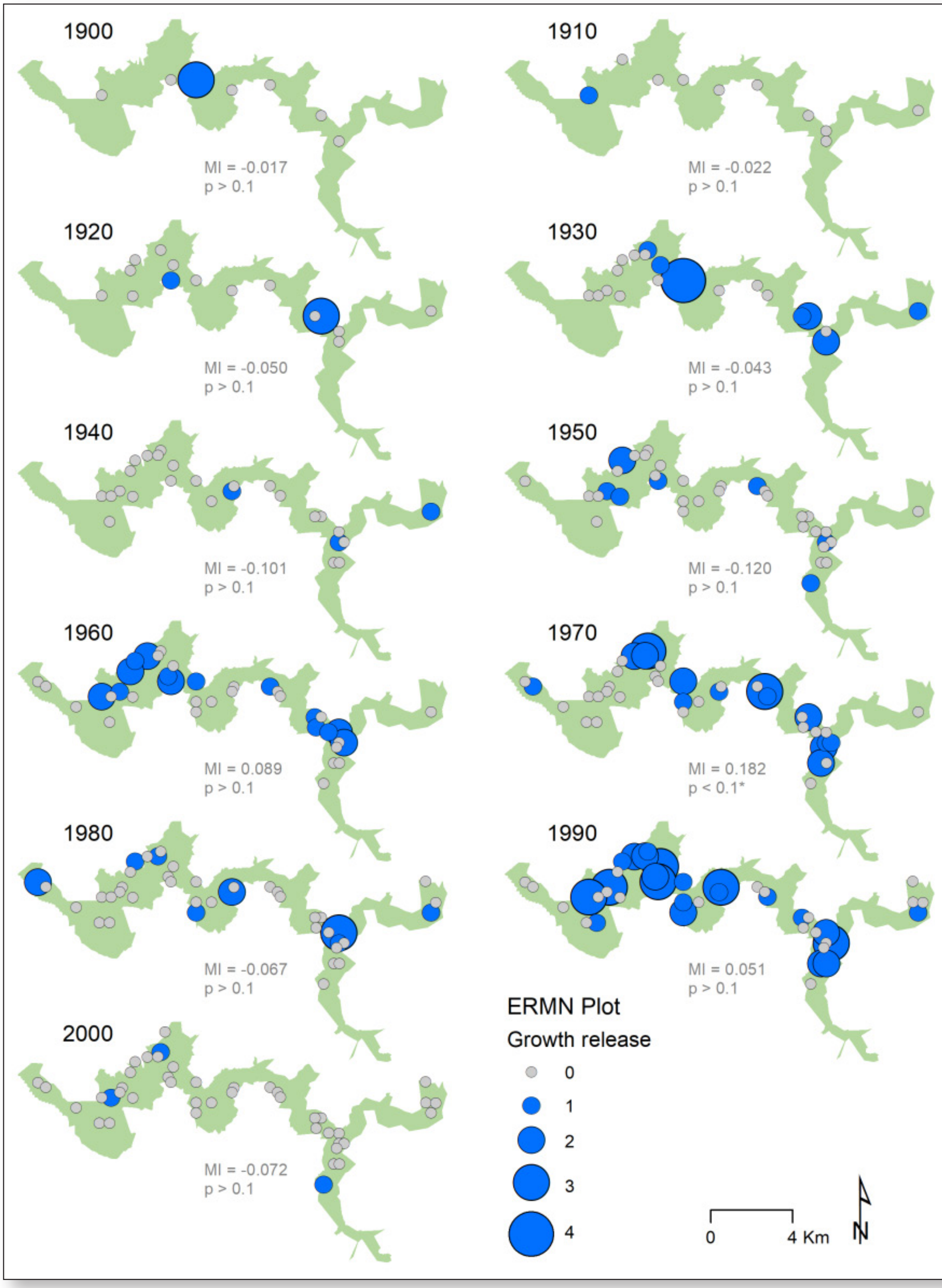

Figure 11. Spatiotemporal patterns of canopy gap disturbance (i.e., total number of tree-level growth releases per plot) at Gauley River National Recreation Area (GARI). Moran's Index (MI), a measure of spatial autocorrelation, is indicated for each decade. Data for the most recent decade (2000) should be interpreted with caution since this time period does not include the full analysis window for radial growth averaging.

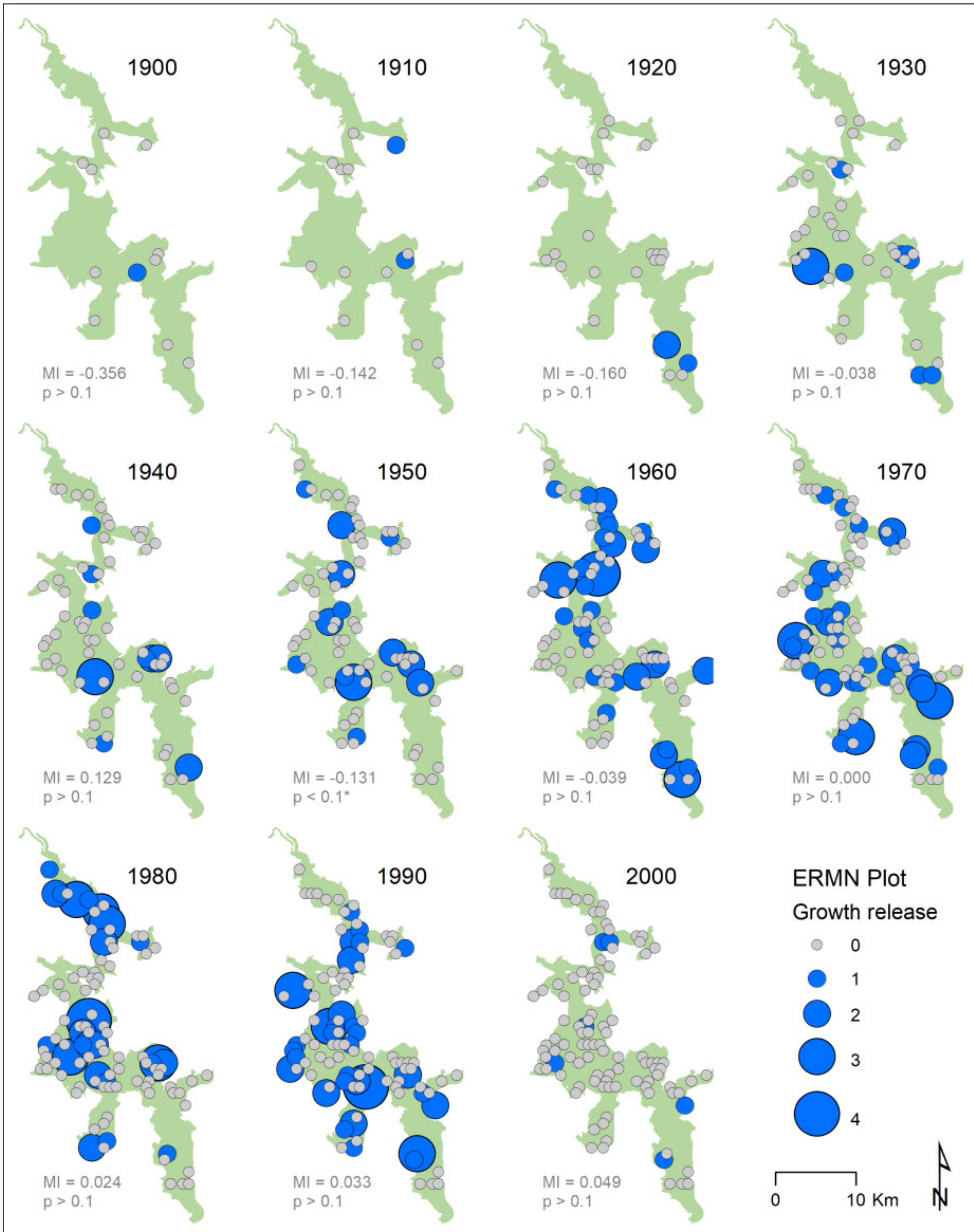

Figure 12. Spatiotemporal patterns of canopy gap disturbance (i.e., total number of tree-level growth releases per plot) at New River Gorge National River (NERI). Moran's Index (MI), a measure of spatial autocorrelation, is indicated for each decade. Data for the most recent decade (2000) should be interpreted with caution since this time period does not include the full analysis window for radial growth averaging.

Temporal patterns of canopy gap disturbance varied across park units as well (Figure 13). The percentage of plots recording a growth release peaked during the 1930s at BLUE, during the 1990s at GARI, and during the 1960s and 1970s at NERI. For all plots combined, canopy gap disturbance was most extensive during the 1930s, 1960s, 1970s, and 1990s (Figure 13). Chi-square goodness of fit tests indicate that the percentage of plots recording a growth release did not fit expected distributions for each park unit individually and for all plots combined (Figure 14). Most notably, canopy gap disturbance was more extensive than expected during the 1930s and less extensive than expected during the 1950s and 1980s at BLUE ($\chi 2 = 57.23$, df = 10, $p < 0.01$) (Figure 14a). At GARI, canopy gap disturbance was less extensive than expected during much of the 20th century, but more than expected during the 1930s, 1960s, 1970s, and, especially, the 1990s ($\chi 2 = 73.33$, df = 10, $p < 0.01$) (Figure 14b). Similarly, at NERI, canopy gap disturbance was less extensive than expected until the latter half of the 20th century ($\chi 2 = 28.80$, df = 10, $p < 0.01$) (Figure 14c). The dominant patterns across individual park units are highlighted when all plots were combined, indicating that the canopy gap disturbance was more frequent than expected during the 1930s, 1960s, 1970s, and 1990s ($\chi 2 = 26.36$, df = 10, $p < 0.01$) (Figure 14d).

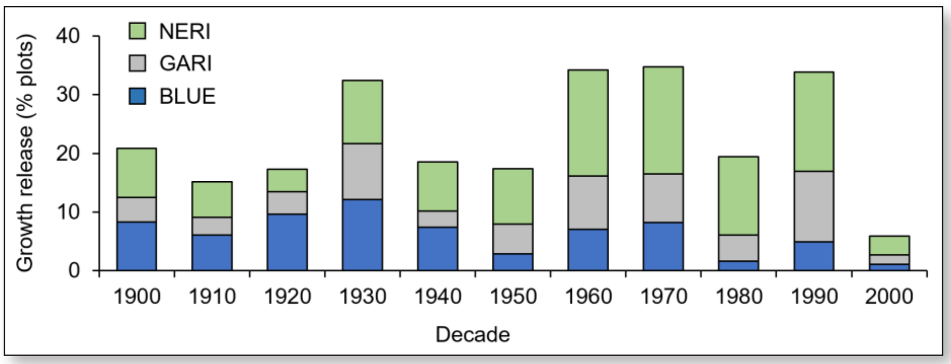

Figure 13. Percentage of Eastern Rivers and Mountains Network plots recording a growth release by decade. Data for the most recent decade (2000) should be interpreted with caution since this time period does not include the full analysis window for radial growth averaging.

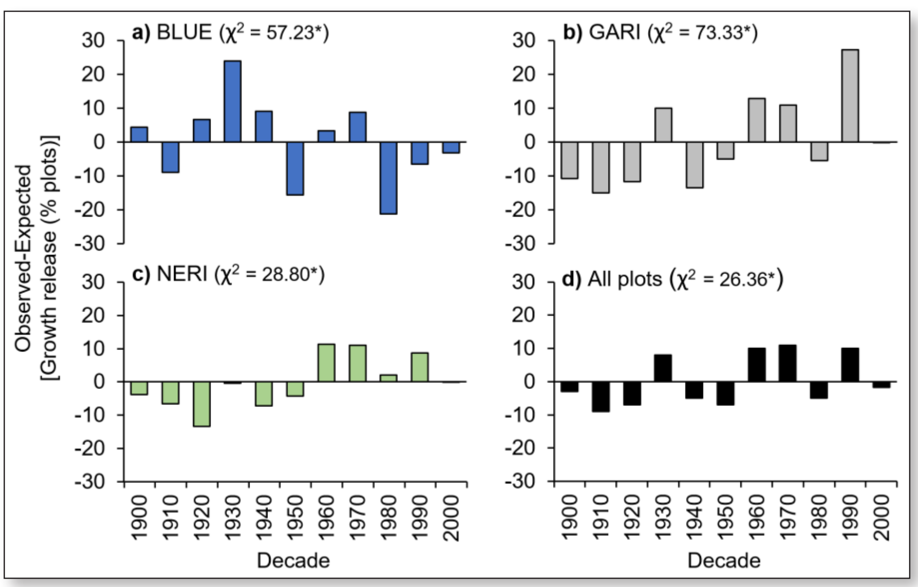

Figure 14. Observed minus expected percentage of Eastern Rivers and Mountains Network plots recording a growth release by decade. Data shown are the results of Chi-square goodness of fit tests for each park unit and the three park units combined (df = 10, *$p < 0.01$). Expected values were assumed to be equal across decades in proportion to the number of years in each decade. Positive values indicate "more than expected," while negative values indicate "less than expected."

Chi-square goodness of fit tests indicate that the number of growth releases did not fit expected distributions across ELUs ($\chi 2 = 44.02$, df = 10, $p < 0.01$) (Figure 15). In other words, canopy gap disturbance was dependent on ELU, with a greater than expected number of growth releases per tree occurring at plots in the "Cliff," "Steep Slope," and "Upper Slope" ELUs and fewer than expected occurring at plots in all other ELUs.

As stated earlier, canopy gap disturbance at NERI peaked during and after the 1960s. Interdecadal trends indicate that this timing lags behind peak wildfire occurrence and extent and also corresponds to the more recent period of increased regional moisture availability (Figure 16).

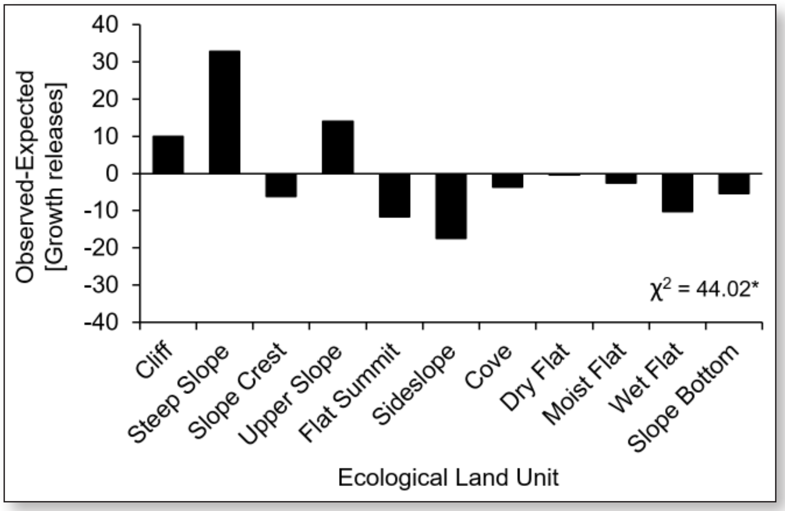

Figure 15. Observed minus expected number growth releases for all Eastern Rivers and Mountains Network plots stratified by Ecological Land Unit (ELU) (NRAC, 2012). Data shown are the results of a Chi-square goodness of fit test where expected values were assumed to be equal across ELUs in proportion to the number of plots in each ELU class (df = 10, $p < 0.01$). Positive values indicate "more than expected," while negative values indicate "less than expected."

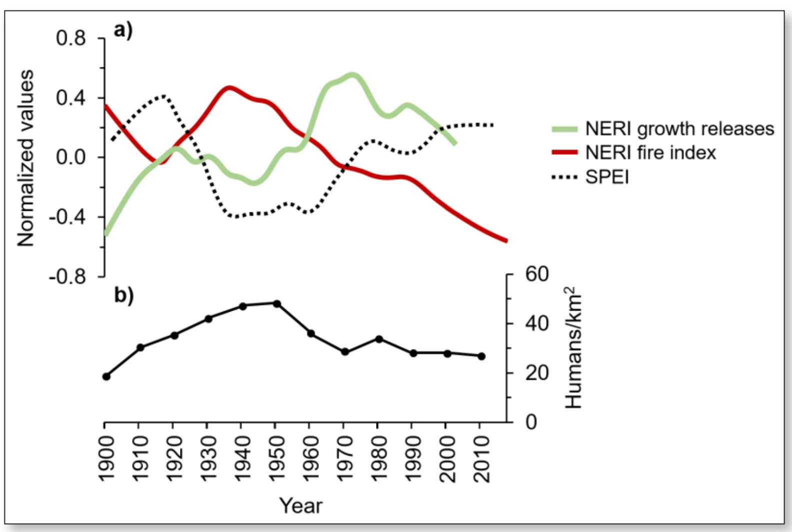

Figure 16. Interdecadal trends in canopy gap disturbance, fire, drought, and population density at New River Gorge National River (NERI): a) Percentage of samples recording a growth release at NERI, composite wildfire occurrence and extent for three fire history sites at NERI (Saladyga et al., 2019), and the regional annual Standardized Precipitation Evapotranspiration Index (SPEI). Normalized values (z-scores) are smoothed using locally weighted regression (s = 0.30) (Cleveland and Devlin, 1988). b) Fayette County population density (US Census Bureau, 2019).

Discussion

What are the climatic drivers of growth in three dominant tree species, *L. tulipifera*, *Q. alba*, and *Q. prinus*?

Drought (SPEI) is a partial driver of annual ring width in the three dominant species in the parks. Drought can be driven by a decrease in precipitation and/or by an increase in temperature leading to increased evaporative demand. The three dominant species showed a significant response to drought in the current growing season (May – August). The growing season response to drought is a common finding in species growing in the region (Maxwell et al. 2011, 2012, 2017; Saladyga and Maxwell, 2015). In the previous growing season, the months of September and October were significantly related to ring width (varied by species) indicating that photosynthesis in the latter half of the previous growing season contributed to carbohydrate storage and use in the following growing season. Lagged relationships between climate and tree growth are common as some species rely on stored carbohydrates to begin biomass production in the following year (Cook and Kairiukstis, 2013).

How have climate-tree growth relationships changed over time?

The moving correlation analysis indicated that the dominant Quercus species are becoming less sensitive to SPEI in the current growing season since the 1970s, particularly in the month of June. L. tulipifera maintained a mostly stable relationship to climate over the past century. In the central Appalachian region, June is a key month for the growth of earlywood cells. The decline in sensitivity to SPEI would indicate that trees are no longer stressed by drought or there has been a shift in the limiting factor to growth. The regime shift analysis indicated that the month of June shifted from drier to wetter conditions in the 1990s. The increased moisture during this crucial period of growth might indicate that the trees are no longer limited by moisture. However, a shift from wetter to drier conditions in August might counter the positive effects increased moisture in June. Additionally, spring months appeared to show increased significance in the formation of annual ring width, indicating that trees in the study region may be shifting growth strategies and beginning to grow earlier in the year. Analysis of phenological and dendroband data could provide further insight into the timing of tree growth.

To further complicate the interpretation of the shifting climate response, we found increased significance of SPEI in the previous growing season. This dependence on the previous growing season might represent an adaptive response of trees to a changing climate in which trees draw upon carbohydrates produced and stored in the previous year to mitigate current year deficiencies. The changing growth responses to variations in climate may present challenges for forest adaptation as our climate warms and shifts seasonally in the 21st century. Further investigation of the instrumental climate data is necessary to further determine impacts to regional forests. Additional forward modeling of the tree growth response to climate would be beneficial.

Does the timing and spatial extent of canopy gap disturbance vary across park units or by terrain position?

Our results suggest that patterns in canopy gap disturbance differ between park units and by terrain position. Growth releases were recorded in a larger proportion of samples collected at GARI and these releases were, on average, significantly greater than those recorded in samples collected at BLUE and NERI (see Table 3). These differences might be associated with the steep terrain at GARI, where plots are located on significantly steeper slopes than those at BLUE and on slightly steeper slopes than plots at NERI (see Table 2). Slope steepness is important for interpreting these results because we found that a greater than expected number of growth releases occurred at plots in the "Cliff," "Steep Slope," and "Upper Slope" ELUs (see Figure 15). This is likely due to tree fall and gap formation being more common on steeper slopes where soils are thin and mass wasting (i.e., soil creep and landslides) occurs with greater frequency and intensity compared to gently sloping and flat terrain. However, we are limited in this interpretation by the small sample size at each plot (≤ 2 trees) and the fact that only the survivors are included in the dataset.

We found no significant clustering or dispersion of canopy gap disturbance (i.e., growth releases) during most of the decades analyzed, with the exception of the 1920s, 1950s, and 1970s (see Figures 10-12). Spatial clustering at BLUE during the 1920s and 1970s and at GARI during the 1970s indicate that gap formation was not random and likely caused by local disturbances (e.g., logging, fire, storms).

Significant dispersion at NERI during the 1950s indicates that plots with dissimilar values (i.e., growth releases) are located near each other. In other words, canopy gap disturbance was non-random and spread evenly across plot locations. The general absence of significant spatial autocorrelation, however, suggests that canopy gap disturbance typically occurred in a random spatial pattern throughout most of the 20th century, which is consistent with patterns of small gap formation in closed-canopy deciduous forests (Foster, 1988; McEwan et al., 2014). These results, however, should be interpreted with caution because Moran's Index is less likely to indicate significant clustering or dispersion within a linear shaped unit of analysis, like the three park units, compared to a square area.

The spatial extent of canopy gap disturbance, or percentage of plots recording a growth release, differed between park units and across decades (see Figures 13 and 14). As such, it is unlikely that a landscape-scale, or region-wide, disturbance occurred during the 20th century. At BLUE, canopy gap disturbance was unexpectedly extensive during the 1930s, which might be associated with the arrival of Chestnut blight and/or increased logging activities in the area at that time. At GARI, canopy gap disturbance was more extensive than expected during the 1990s, but it is difficult to hypothesize about the potential driver(s) of this pattern. GARI was established as a unit of the NPS in 1988, and most of the land within the park's designated boundary was privately owned when the park was established. Logging activities could have increased on private lands after the park was enacted before lands were transferred to the government. It is unlikely that the increased gap formation in GARI in the 1990s was caused by hemlock mortality since hemlock woolly adelgid (Adelges tsugae Annand) was not detected in Fayette and Nicholas Counties until 2002 (WVDF 2010). At NERI, the extent of canopy gap disturbance was minimal until the second half of the 20th century. Forests that were cleared during the industrial era (ca. 1870s-1920s) succeeded into closed canopy forests by this time as a result of deindustrialization, population loss, and general exclusion of disturbances, including fire (see Figure16). This would increase the likelihood that spatially random gap dynamics typical of closed canopy forests are detected in the tree-ring record. These results should again be interpreted with caution due to the small sample size at each plot as well as limited disturbance history data at NERI (Saladyga, 2017; Saladyga et al., 2019) and no fire history data available at BLUE or GARI.

Based on our results, what additional research questions might be addressed with more systematic data collection, either at the landscape or local scale?

Our analysis would benefit from a more systematic collection of tree cores to address the key questions posed in this report. Targeting species with low representation in the data set (e.g., eastern hemlock, eastern white pine, and red maple) would provide a fuller understanding of the variable response of tree species to changes in climate both past and present. A second method for expanding the analysis would be to include tree core data from throughout the central Appalachian region. Previous research indicates that climate is not changing uniformly throughout the eastern United States and the larger effect on forest growth is unknown. In addition, systematic sampling (e.g., large plots) would be necessary to improve our understanding of past disturbances at multiple spatial scales.

Conclusions

Our results indicate that trees are responding to current and previous growing season moisture conditions, but the stability of these relationships has varied over time by species. These changing growth responses to variations in climate might present challenges for forest adaptation as our climate warms and shifts seasonally in the 21st century. Conversely, the ability of trees to shift their growth response to climate might be adaptive, providing some resilience in the coming century. Also, the results discussed above suggest that dominant patterns of canopy gap disturbance were not synchronous across park units and that gap formation occurred in predominantly random spatial patterns. In addition, the notably steep terrain found within the parks, especially at GARI, seems to have a strong influence on gap dynamics. While we were able to better understand how past landscape disturbances and climate affected tree growth, we realize that the sampling regime used in inventory plots is not optimal. Systematic sampling, including large plots (e.g., 4 ha) stratified by terrain position and/or forest type would improve our ability to answer the key questions posed in this report. The goal of future sampling should be to better understand the resiliency of tree species to changes in climate and patterns of forest disturbance across more sites with greater sample depth

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